REMARKS

Claims 10, 13, 14, and 17-24 are all the claims pending in the application. Claims 10, 14, 18, and 21 have been amended based on, for example, page 7, lines 28-31 of the specification. Claims 11 and 15 have been canceled.

Entry of the above amendments is respectfully requested.

Claims 10-17 and 24 are rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bangaru et al. (US 6,228,183) in view of Heitmann et al. (US 5,554,233).

In addition, claims 18-23 are rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Heitmann et al. (US 5,554,233) in view of Bangaru et al. (US 6,228,183).

Applicants respectfully traverse the rejections for the reasons of record and the following reasons.

It is respectfully submitted that the claimed process provides for a forged steel product possessing desired properties without any thermic treatment at the end of the forging. Accordingly, the claimed process is completely opposite to Bangaru.

Indeed, Bangaru teaches that a hard forced cooling (i.e. a quenching) of the steel (which is here a steel plate, then not a long steel product as the object of the invention) is necessary to obtain the desired bainite microstructure (*see* ref. 24 in Fig. 1 of Bangaru) which is known to be able to give the final steel product with the desired properties.

More precisely, at column 3, lines 30-51, Bangaru considers a new process, called IDQ, which teaches a quenching of the hot laminated steel product at the end of its rolling in the austenitic area in two consecutive steps: a first step of hard cooling, then with water (*see* ref 12 of Fig. 1 of Bangaru) until the point under ref 16, about 400°C, followed by a second step of soft cooling (with air) until the ambient temperature when the microstructure is in the bainitic domain 20 (*see* branch 18 on Fig. 1 of Bangaru). Because of that, the way the microstructure

transformations during the cooling of the steel after hot rolling before the noze of the ferrite-perlite area (ref 26) in the first time, in order to develop a uniform lower bainite in the second time, as clearly showed on Fig. 1 of Bangaru.

Due to the claimed steel composition, a forced cooling of the hot rolling laminated long steel product having the claimed composition is not necessary, nor recommended, after its hot rolling in the austenitic area to obtain the desired microstructure of bainite given the desired properties on the final piece ready for use. Indeed, with the claimed steel composition, the ferrite + perlite area (ref. 26 on fig 1 of Bangaru) does not exist. Only the desired bainitic domain (ref. 24 on Fig. 1 of Bangaru) is present.

As a consequence, in the claimed process, only a simply cooling by air until ambient temperature can be made at the end of the hot rolling in the austenitic range (namely, no formation of perlite has been observed even with a cooling rate lower than 0.1°C/s (33.8 °F/s)). This represents a great advantage of the claimed invention over Bangaru.

Moreover, the Examiner's attention is drawn to Fig. 1 of the article published in 2007 titled "New Bainitic Steels for High Strength Components for Automotive Parts" (submitted herewith), where as in hot forging mode (left part) or in cold working mode (right part), it can be seen that the steel grade of the claimed invention (named HSLA) permits the by-pass of several steps of the classical way of working of mechanical components.

For at least the above reasons, it is respectfully submitted that the present invention according to claims 10, 14, 18, and 21 is patentable over the cited art.

Moreover, claims 13, 17, 19-20, and 22-24 depend from claims 10, 14, 18, or 21, and thus it is respectfully submitted that these claims are patentable for at least the same reasons as claims 10, 14, 18, and 21.

In view of the above, withdrawal of the rejection is respectfully requested.

II. Conclusion

For the foregoing reasons, reconsideration and allowance of claims 10, 13-14, and 17-24 is respectfully requested.

If any points remain in issue which the Examiner feels may be best resolved through a personal or telephone interview, the Examiner is kindly requested to contact the undersigned at the telephone number listed below.

The USPTO is directed and authorized to charge all required fees, except for the Issue Fee and the Publication Fee, to Deposit Account No. 19-4880. Please also credit any overpayments to said Deposit Account.

Respectfully submitted,

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New Bainitic Steels for High Strength Components for Automotive Parts

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ABSTRACT

The production of high strength components by cold heading, cold forging or hot forging without final heat treatment has been made possible by the development of micro-alloyed steels. Among the different types of steel available for this purpose, the low carbon bainitic grades appear the most promising for the production of parts where both high strength and ductility are required when the conditions for use are considered. In order to extend the range or size of parts having bainitic structures capable of being produced, new low carbon grades of micro-alloyed steel have been developed with niobium. This family of grades is called FREEFORM ™.

INTRODUCTION

For cold heading and hot forging processes, the elimination of the post heat treatment operations is the point where substantial cost savings requested by the OEM's (Original Equipment Manufacturers) can be the most readily obtained .

The production of components by cold heading without any heat treatment or by hot forging and direct quenching has been made possible by the development of micro-alloyed (HSLA) steels (Fig.1). Precipitation hardened ferrite-pearlite medium carbon micro-alloyed steels have been developed over the last three decades for this purpose [1-5].

Moreover, the CAFE (Corporate Average Fuel Economy) standards require weight reduction for cars or light trucks. One of the solutions is downsizing automotive components providing that high strength materials are used. However, it is difficult to strengthen ferrite-pearlite over 1000 MPa without increasing carbon level and yet maintaining enough toughness as needed for selected automobile parts. Inversely, a decrease of carbon is effective in improving toughness but it causes an important loss of strength in ferrite-pearlite steels. Thus, this type of grade could not be widely applied to produce components which require high strength, high ductility and high toughness [6-9].

Due to its low temperature formation, bainite has higher strength than ferrite pearlite steels with the same carbon content [6-8]. Therefore, the requested strength may be obtained with a lower carbon content. The low carbon bainitic grades appear to be the most promising for the production of parts with a good combination of strength, ductility and high toughness.

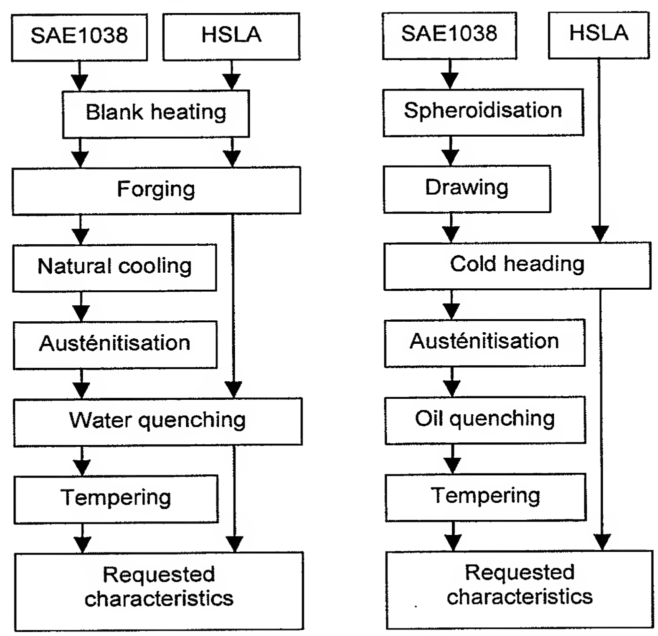


Fig. 1. Schematic manufacturing process evolution of hot forged and cold headed parts.

Several chemistries [10-14] have been proposed by steel makers to obtain a bainitic structure with a carbon level equal or less than 0.1% in weight percent [9-13]. The most common grades currently used are alloyed with chromium and manganese [11-13].

Nevertheless, the bainitic structure, and consequently the optimum mechanical properties, can only be attained if the cooling rate is above a critical value depending on the hardenability achieved from the chemistry of the steels proposed.

The hardenability of most of the grades currently proposed leads to the following consequences:

- for cold heading without final heat treatment, the application must be limited to the production of parts from as-rolled rod of a small diameter.

- in the case of hot forging and direct quenching without tempering using water as the quenchant, a specific tempering process must be used to avoid distortion of the parts. Furthermore, using this type of grade to produce large parts or ones with locally thick sections could result in significant variation in the structural and mechanical characteristics of the parts.

In order to extend the range of parts with high strength bainitic structures capable of being produced by cold heading or hot forging without final heat treatment, new low carbon grades microalloyed with niobium have been developed.

EXPERIMENTAL PROCEDURE

The new grades presented in this paper were developed following procedures established at the Mittal Steel Europe R & D Centre dedicated to long products.

After identification of the function and properties of the final part selected, the material properties needed to achieve these final objectives were then clearly defined. Several chemical compositions were proposed based on the expertise and data base of Mittal Steel. The potential of the different grades that were proposed were evaluated using software developed in the laboratory from either statistical or internal metallurgical models.

Small ingots weighing 30 to 40 kg (66 to 88 lbs) having defined compositions and validated previously were then prepared through the use of a vacuum furnace.

The procedure used to characterize the potential of the grade tested depends on the targeted application.

- **Cold heading or cold forging application**

The laboratory ingots were welded to a billet and rolled under industrial conditions (Table 1) to obtain wire or bars with the desired diameter. This method provides several advantages:

- it is closely representative of the industrial process and, thus, may determine not only the influence of chemical composition but also the influence of the rolling parameters,

- it is possible to carry out semi-industrial trials with cold heading makers.

In the present case, the objective was to obtain the mechanical properties required on parts by simple work-hardening of the steel. So the potential of the grades tested was determined by cross sectional reduction of the wires using a drawing bench in order to determine the stress-strain behavior. This permits an estimate of the cross-sectional reduction necessary to fulfill the tensile strength requirements and to estimate the cold formability of these steels.

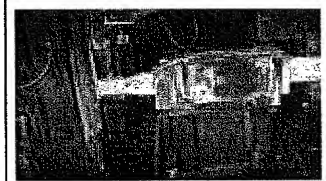
	
Ingot weld to a billet	rolling of the ingot

Table 1 Method for obtaining bar or wire from laboratory ingots.

- **Hot forging application.**

The ingots were directly rolled into bars to the final section required.

The potential of forging the grade was demonstrated by preparing components on the EDK 600 hydraulic press at CER ENSAM in Metz (FRANCE) .

The tooling that was used consisted of two stations. It was an integral part of a protocol developed jointly by the laboratory at Mittal and CER ENSAM to compare materials for producing forged and machined components [14].

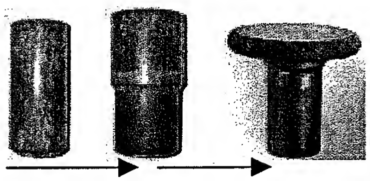
The forging operation is carried out on a 43.5 mm diameter, 133.8 mm long cylindrical blank that can be induction heated (for hot forging) or not heated (for cold deformation). The two forming operations use extrusion (± 20% reduction in section) followed by upsetting (±72% compression) (Table 2).

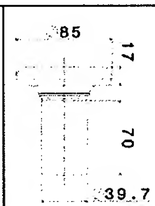
The geometry of the forged part is close to that of a stub axle. The dimensions were defined so as to be able to undertake significant forging campaigns using a relatively small amount of metal while at the same time enabling subsequent machining and residual stress analysis.

The parts are designed to allow samples to be cut for microstructural analysis as well as for tensile and impact testing. The influence of high temperature plastic strain on the final structures can also be evaluated. The component shape is close to that of industrial practice than more conventional test-pieces while remaining moderate in size (1.5 kg). In addition, mechanical tests (as bend tests, fatigue tests or other test applications) can be assessed from the forged part.

If the desired properties of the part can not be simulated by this process, heat treatments can be directly performed on the forged bars.

In all cases, the final step was directed toward the characterization of the parts using accepted methods.





Extrusion Upsettting | Dim. in mm

Table 2. Operations performed to produce cold or hot forged samples.

LOW CARBON BAINITIC STEEL GRADES FOR COLD HEADING OR COLD FORGING APPLICATIONS

The objective was to obtain the mechanical characteristics of class 10.9 fastener as defined by ISO 898.1 standard (UTS > 1000 MPa; YS > 900MPa; El > 9% ; RA > 48%) by simple work hardening of the steel.

The mechanical behavior of parts obtained by simple work hardening instead of an expensive heat treatment depends on several factors which are all interdependent: mechanical characteristics of the wire rod, stress-strain coefficient of the steel grade, cold heading process used by the customer and notably the cross-sectional reduction to be used on the wire rod.

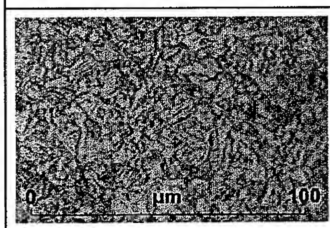
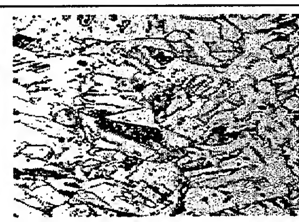
Wire rod Ø8 mm				Wire rod Ø 14mm			
 Granular bainite				 Degenerated structure			
TS MPa	YS MPa	EL %	RA %	TS MPa	YS MPa	EL %	RA %
800	591	20.5	66	635	463	25.5	63
Mechanical characteristics requested by 10.9 class							
reached after 35%				not reached			

Table 3. Influence of the diameter of wire on the structural and mechanical characteristics of a low carbon bainitic grade alloyed with chromium and manganese.

In the case of the low carbon grades considered for this study, the required mechanical characteristics of the wire rod and stress-strain coefficient of the steel grade are essentially due to the bainitic structure of the steel. This could lead to the production of high strength parts over a range of deformation levels used by cold heading manufacturers.

Obtaining this type of structure depends on the hardenability of the grade and also on the cooling rate of the wire at the end of the rolling process. This cooling rate is also dependent on the wire diameter.

Table 3 shows that, given a certain diameter, the proposed grades alloyed only with chromium and manganese cannot achieve the bainitic structure on the wire rod and, therefore, it is not possible to reach class 10.9 by work hardening,

To extend the diameter of wire having a bainitic structure and to reach the mechanical characteristics of class 10.9, Mittal Steel has decided to develop another type of low carbon bainitic steel grade family called Freeform™ Grade which has been divided into two sub-families called: Freeform™ 10.9 and Freeform™ IT (Improved Toughness).

FREEFORM ™ GRADE

The Freeform™ grade was initially developed [14] for the production by cold heading without final heat treatment of high strength parts corresponding to class 9.8 (ISO 898-1). Like most grades without final heat treatment, it is particularly designed for the production of long parts, such as knuckle joints, long screws, etc.

Freeform™ is a low carbon bainitic steel micro-alloyed with boron and niobium (Table 4)

	C	Mn	Si	Nb	B	Mo	Ti	Al
Min.	100	1350	200	50	1	10	8	20
Max.	140	1600	350	100	4	100	20	30

Table 4. Nominal composition of the Freeform™ grade as designated in the patent (weight percent x 1000).

- The combination of niobium and boron enables the rate of ferrite nucleation to be significantly reduced, leading to the formation of a wide bainite domain [16].

The effect of boron alone is well known. It retards ferrite nucleation by segregating to the austenite grain boundaries. However, only uncombined boron is active in this way. By stabilizing the austenite and retarding carbon diffusion, niobium increases the quantity of active boron, limiting or eliminating the formation of boro-carbides of the type $Fe_{23}(CB)_6$ which otherwise tie up boron [17].

Niobium also promotes the attainment of a fine bainitic structure in the wire rod [18], thus increasing the toughness.

- The aim of the titanium addition is to protect the boron by preventing it from combining with nitrogen. In the form of TiN, it also prevents excessive growth of the austenite grains at the high reheating temperatures necessary to take the niobium precipitates into solution [18].

- Molybdenum, in association with manganese and niobium, promotes the formation of a fine bainitic microstructure by lowering the bainite start temperature, Bs [17]. It also enhances the synergetic effect of niobium and boron by increasing the solubility of niobium in the steel.

- Manganese contents between 1.5-2% increase strength without reducing toughness [19].

FREEFORM ™ 10.9 GRADE

Using the technical procedure described previously with an optimization of the chemistry of Freeform™ and the rolling process parameters, it is possible to produce wire rod with a high strength homogeneous bainitic structure over a range of diameters 5.5 mm to 18 mm (0.2165 to 0.7087 inches) (Table 5).

The type of bainite obtained is dependent on the diameter of the wire rod. The wire of smaller diameters are comprised of a mixture of bainite I, bainite II and bainite III as defined by Ohmori [20]. When the diameter of the wire increases, the proportion of lower and upper bainite decreases and for the larger diameters the structure is composed almost exclusively of granular bainite.

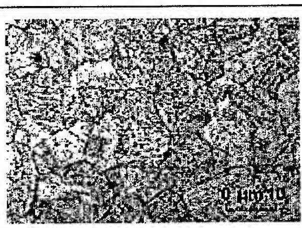
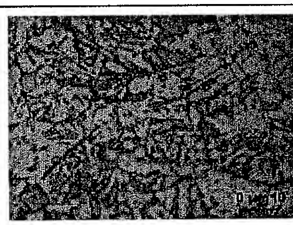
Freeform™ 10.9 Ø 6 mm		Freeform™ 10.9 Ø18 mm		
				
Wire rod	TS MPa	YS MPa	EL %	RA%
Ø 6 to18 mm	880-750	730-600	24-19	68-62
10.9 class properties obtained after 15-45%				

Table 5. Influence of the diameter of Freeform™ 10.9 wire rod on structure and mechanical properties.

Tables 5 and 6 show that by using this type of grade, it is possible to produce parts from all the wire diameters investigated up to 18 mm (0.71 inches) with mechanical properties meeting class 10.9 specifications through work hardening of the steel without using a final heat treatment. The strain hardening that is necessary to reach the requested mechanical properties is dependent on the diameter of the wire but it needs to be in the range of those used by bolt makers (Table 5).

Investigations with FEG-SEM as shown in Table 6 indicate that the homogeneous structure obtained on a Freeform™ wire of Ø 12 mm is almost exclusively granular bainite (bainite I) characterized by the absence of carbides and the presence of islands composed of retained austenite and martensite/austenite (M/A phase). Nevertheless, it has been noted also that there are very small areas of bainite III.

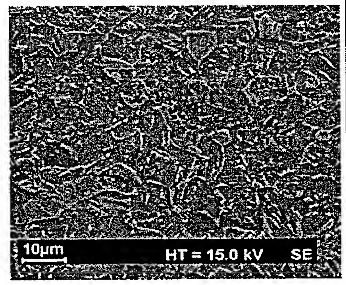
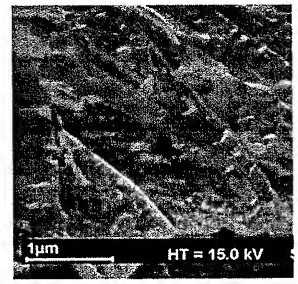
A			B	
				
Wire rod	TS (MPa)	YS (MPa)	EL %	RA%
Ø 12 mm	820	625	18.5	64.5
10.9 class properties obtained after 35% deformation				

Table 6. Mechanical characteristics and microstructures of Freeform™ 10.9 wire (12 mm) observed by FEG-SEM .(a) granular bainite (I) , (b) low bainite areas (bainite III).

The potential of the Freeform™ 10.9 grade has been confirmed on industrial components such as long steering rods. For this type of product the use of a work hardening steel presents the advantage of avoiding distortion and, also, a costly straightening and stress relieving operation.

The results obtained from a Freeform™ 10.9 wire having a starting diameter more than 15 mm were compared with those obtained from a 38Cr4 pre-quenched grade. This grade was developed, in fact, in the latter half of the 1970's where the heat treatment is still required. Therefore, in order to simplify the cold heading process the quench and tempering treatment is performed directly on the wire rod. The structure obtained is a tempered martensite. This type of pre-treated grade is considered, up to now, as a reference grade in the cold heading or cold forging process where the mechanical properties of the parts are achieved by work hardening.

The behavior of the parts that have been produced shows that the material flow is similar (Table 7) for these two types of grades. The formability of the low carbon bainitic structure obtained from Freeform™ 10.9 indicates that the ductility is similar to that of the tempered martensite structure. It must be noted that for the two steel grades that are compared here the elongation and reduction of area have been found close to 25% and 70%, respectively, for a ultimate tensile strength close to 760 MPa.

Table 8 shows a comparison of the Vickers micro hardness profiles obtained on the head and shank of a ball stud produced from Freeform™ 10.9 and 38Cr4 pre-quenched steel grades. The micro hardness values found on part from Freeform™ 10.9 are, at least, of the same order as those obtained from the 38Cr4 pre-treated steel grade. The microhardness gradient observed within the profile curve and the difference between profile curves obtained from the head or shank

reflect the variation in deformation of the wire and is inherent to the cold heading process without heat treatment.

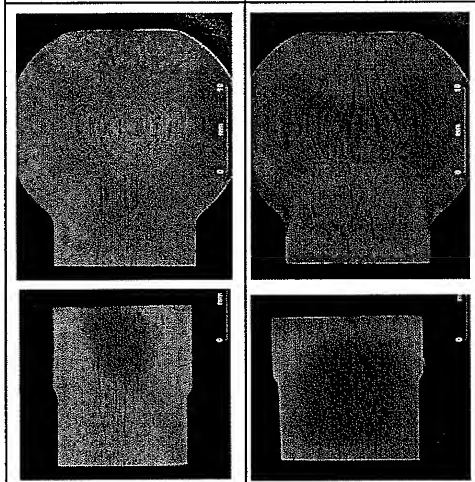
Freeform™	38C4 pretreated
	

Table 7. Material flow in head and shank of a steering rod.

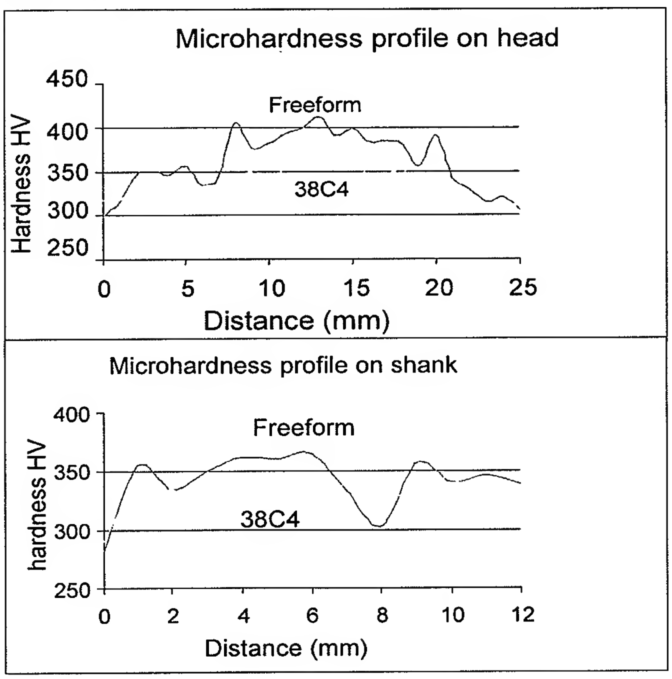
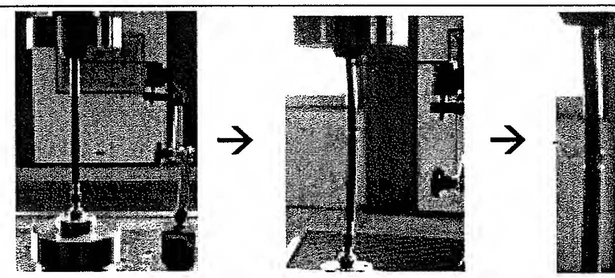


Table 8 Comparison of the Vickers micro hardness in head and shank of a steering rod produced from Freeform™ 10.9 and pre-quenched 38Cr4 steel grades.

Due to the variety of conditions that may be seen by steering rods in service, an important characteristic required on this type of part is a resistance to buckling. Laboratory tests, illustrated in Table 9, have been conducted to determine the force required to flex to 0.1 mm followed by test to rupture of the part. The axis of this part initially presents a little deviation with regard to the direction of the force applied.

The results obtained show that the buckling resistance of the part produced from Freeform™ 10.9 are at least equivalent to that of the part produced from the pretreated 38Cr4 steel grade.



Freeform™ 10.9 grade		prequenched 38C4 grade	
$F_{rupture}$	$F_{0.1mm}$	$F_{rupture}$	$F_{0.1mm}$
62470 N	48150 N	60700 N	41900 N

Table 9. Buckling test: Comparison of the buckling resistance of parts produced from Freeform™ 10.9 and pre-quenched 38Cr4 steel grades.

Furthermore, it must be noted that fatigue tests carried out by an industrial manufacturer showed that the parts produced from Freeform™ 10.9 provide better results as compared to those of pretreated 38Cr4 steel grade.

Finally, in terms of machinability the tests performed on parts showed that Freeform™ has good chip breakage behavior, enabling the fragments to be readily removed with the coolant.

FREEFORM™ IT (IMPROVED TOUGHNESS)

The Freeform™ IT grade was developed as a cold heading steel grade for safety related applications without the need for final heat treatment. This grade combines both high strength that meet the requirements of 10.9 class fasteners with very good toughness.

The chemical composition is based on that of the Freeform™ grade and was optimized to improve the toughness (Table 10).. The carbon content has been lowered to avoid the formation of martensite which reduces toughness, while the levels of the other elements have been adjusted to enhance both their individual and synergetic effects. The hardenability has been increased to promote the formation of a fine non-granular bainitic structure.

The CCT diagram of Freeform™ IT steel grade (Fig. 2) shows a large bainitic domain. The formation of pearlite has not been observed for cooling rates lower than 1°C/s (33.8°F/s). For the highest cooling rates investigated, the presence of a martensitic transformation could not be detected by means of dilatometry.

	C	Mn	Si	Nb	B	Mo	Ti
Min.	20	1300	150	40	1	100	>3.5 N
Max.	150	2000	1300	100	5	350	

Table 10 Nominal composition of the Freeform™ IT grade as designated in the patent WO2004050935 [21] (Weight % x1000).

Another factor in the CCT diagram is the lower bainitic start temperature cooling rates of wire processed at the end of rolling mill (diameters of up to Ø 18 mm). This indicates the formation of a fine bainitic structure, as confirmed by optical microscopy investigations on a Freeform™ IT wire rod with a diameter of Ø 12 mm (Table 11).

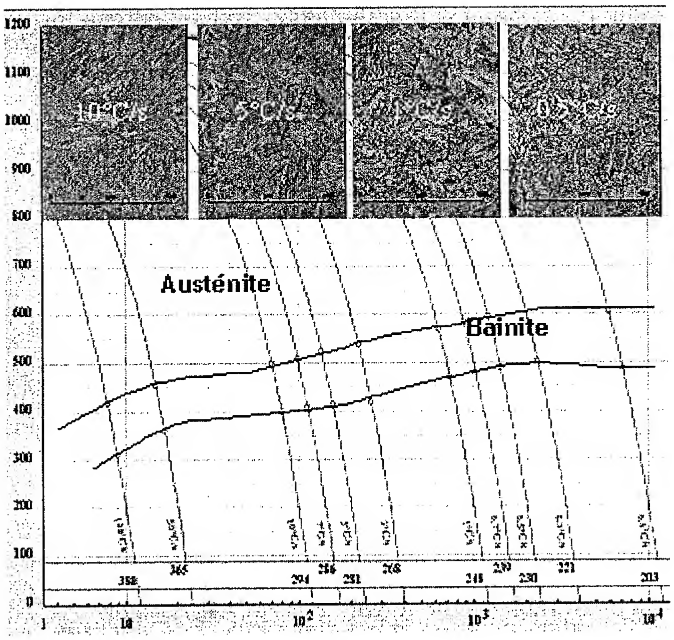
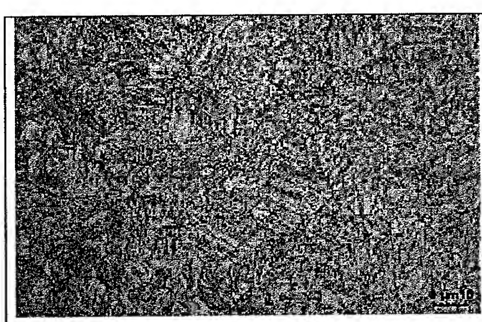


Fig. 2. CCT diagram of the Freeform™ IT steel grade.



	KV J/cm²
20	188
0	195
-20	178

Table 11. Low bainitic microstructure and toughness variation as a function of Freeform wire rod over a series of temperatures.

A FEG-SEM characterization of a Freeform™ IT wire rod with a diameter of Ø 12 mm (0,47 inches) shows a very homogeneous structure almost exclusively composed of lower bainite (bainite III) as shown in Table 12. The microstructure consists of packets of fine parallel ferrite laths and the presence of intra lath precipitates. These plate like particles are precipitated on a single crystallographic orientation from the primary growth direction of the lath (long dimension of the lath).

Table 13 summarizes the results obtained on a 12 mm diameter wire rod of Freeform™ IT. The high potential of Freeform™ IT is revealed in terms of strength, ductility and impact strength. The mechanical properties of class 10.9 are easily reached for a reduction in the cross section of the wire of approximately 30%.

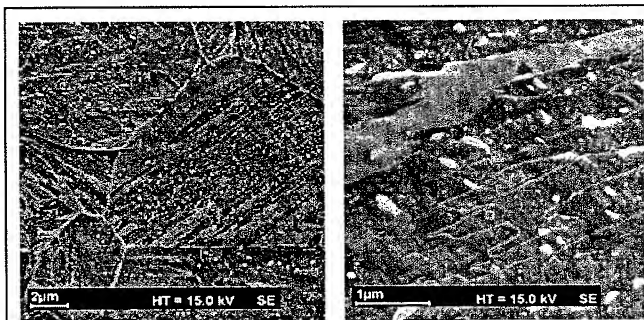


Table 12. Lower bainitic structure (bainite III) of Freeform™ IT wire rod with a diameter of 12mm observed by FEG-SEM.

Ø Mm	Total reduction of section (%)	UTS MPa	YS MPa	El %	RA %
12	0	861	690	18	70
11.54	7.5	937	881	12	69
9.95	31.2	1038	999	12.7	66
8.96	44.2	1096	1014	12.5	64
7.97	55.9	1159	1082	-	64
7.14	64.6	1211	1128	12	63

Table 13. Mechanical property variation of an as-rolled 12 mm diameter Freeform™ IT rod as a function of the strain hardening coefficient (single pass drawing).

It must be noted that there is excellent residual ductility of the wire even after a high cross sectional reduction of the wire. The elongation and reduction in area are never lower than 12% and 63%, respectively, even after more than 60% strain hardening. Consequently, ultimate tensile strength required for class 12.9 (TS > 1200MPa; YS > 1080MPa; El>8%; RA>44%) could be reached for a cross sectional reduction of wire close to 60 % with a residual ductility much higher than requested by standard ISO 898.1.

The toughness of the Freeform™ IT wire rod has been determined by Charpy impact tests using V-notch samples. The values obtained in Table 12 were compared to those obtained from two grades commonly used to produce steering rods or ball studs by cold

forging processes without final heat treatment: a ferrite-pearlite grade (27MnSiV6) and a martensitic tempered pretreated grade (38Cr4) shown in Table 14. It reveals the very high potential of the Freeform™ IT in terms of the impact test. It was observed that the impact toughness of the low bainitic Freeform™ IT grade is, at least, comparable to that of the tempered martensitic grade.

Furthermore, the ductile/brittle transition temperature below -20°C (-4 °F) confirms that the Freeform™ IT grade can be used to produce safety parts.

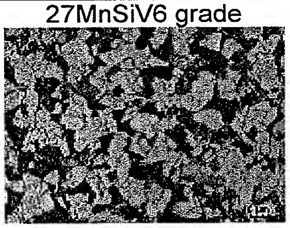
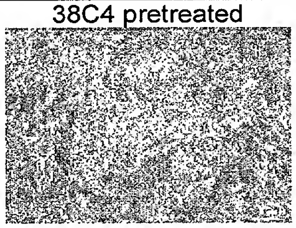
27MnSiV6 grade				38C4 pretreated			
 Ferrite pearlite				 Tempered martensite			
UTS MPa	KV J/cm²			UTS MPa	KV J/cm²		
835	20°C	0°C	-20°C	775	20°C	0°C	-20°C
	87	55	32		167	167	157

Table 14. Microstructure and mechanical properties of wire rod of 27MnSiV6 and pre-quenched 38Cr4 steel grades.

LOW CARBON BAINITIC STEEL GRADE FOR HOT FORGING APPLICATIONS

FREEFORM™ DQ (DIRECT QUENCHED)

The niobium containing microalloyed grade Freeform™ DQ has been developed for applications involving hot forging followed by direct quenching. It is based on a similar chemistry as Freeform™ IT, but was adapted to comply with specific requirements of forging applications.

The potential of this grade was first demonstrated by the production of hot forged components as previously presented.

The Freeform™ DQ blanks were heated to 1200°C (2192 °F) for 20 minutes prior to forging. After forming, the parts were then quenched into two different quenching fluids: water and oil at ambient temperature.

Following the quenching operation, the parts were cut for microstructural analysis as well as for tensile and impact testing.

The results obtained show the significant potential of the Freeform™ DQ grade in the application for hot forging and direct quenching without tempering.

After oil quenching, the tensile and yield strengths of the parts are greater than 1000 MPa and 900 MPa respectively (Table 15).

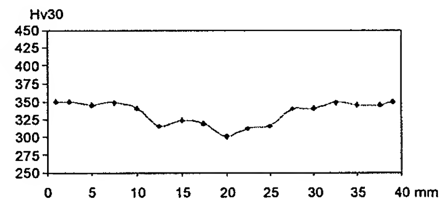
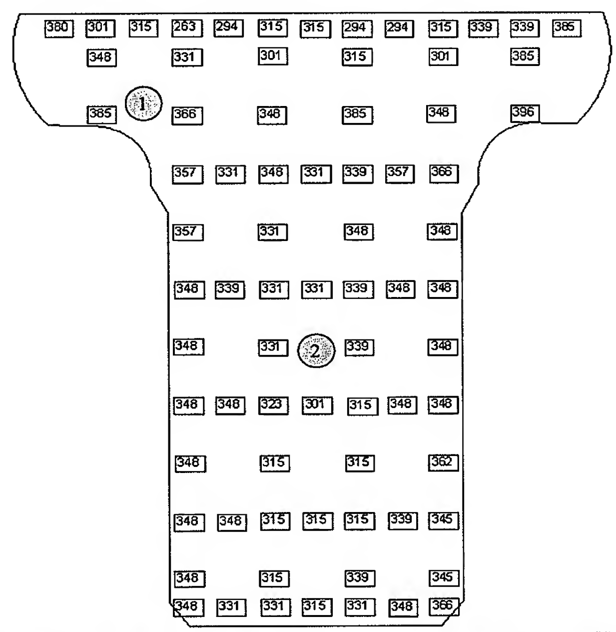
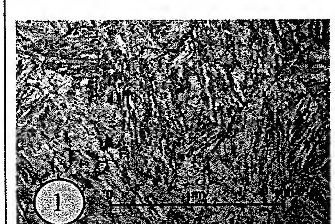
UTS MPa	YS MPa	El %	RA %	KU J/cm²	
1050	925	14	76	20°C	140
				-40°C	105
Hardness HV30 Max. = 350 Min. = 301					

Table 15: Freeform™DQ behavior of the forged part directly quenched in oil.





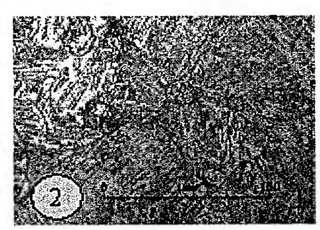


Table 16: Freeform™ DQ showing hardness variations (Vickers tests HV30) and microstructure of the forged part quenched in oil.

This behavior is explained by the fine, non-granular, bainitic microstructure of the part (Table 16) which was defined as a mixture of lower bainite (bainite III) and

upper bainite (bainite II). The FEG SEM investigation revealed the presence of packets of thin parallel laths with intra or inter lath precipitates as shown in Table 17.

The structure obtained is extremely homogeneous (Table 16), as demonstrated by the small hardness gradient (Tables 15 and 16). As expected, this type of structure gives the part a high ductility as seen in Table 16 (reduction of area >75% and elongation > 14%).

The mechanical properties that were achieved are essentially due to the microstructure obtained. This provided a combination of high tensile strength and a quite remarkable impact strength where the KU value remains greater than 100 J/cm^2 at -40°C (-40 °F) (Table 15).

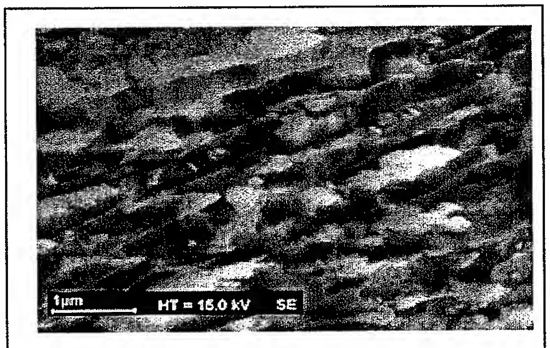


Table 17; Presence of lower and upper bainite revealed by SEM FEG investigations.

After water quenching, the tensile and yield strengths of the parts are even higher at 1200 MPa and 980 MPa, respectively, without the loss of ductility (Table 18) and despite the absence of any tempering treatment. The microstructure is a fine non-granular bainite that promotes a high impact strength of KU > 90 J/cm^2 at 20°C (68 °F) as shown in Table 18. As previously observed for the part quenched in oil, the homogeneity of the structure explains the small hardness gradient that was measured across the part (Tables 18 and 19).

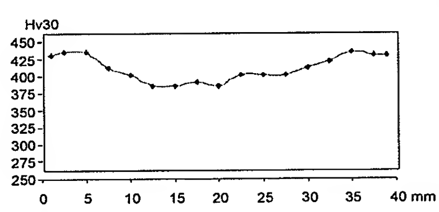
<table>
<tr><td>UTS
MPa</td><td>YS
MPa</td><td>El
%</td><td>RA
%</td><td colspan="2">KU
J/cm²</td></tr>
<tr><td rowspan="2">1200</td><td rowspan="2">980</td><td rowspan="2">14</td><td rowspan="2">73</td><td>20°C</td><td>95</td></tr>
<tr><td>-40°C</td><td>20</td></tr>
<tr><td colspan="6">Hardness (HV 30)</td></tr>
<tr><td>Max. = 435
Min. = 385</td><td colspan="5"></td></tr>
</table>

Table 18: Freeform™ DQ: Behavior of a forged part directly quenched in water.

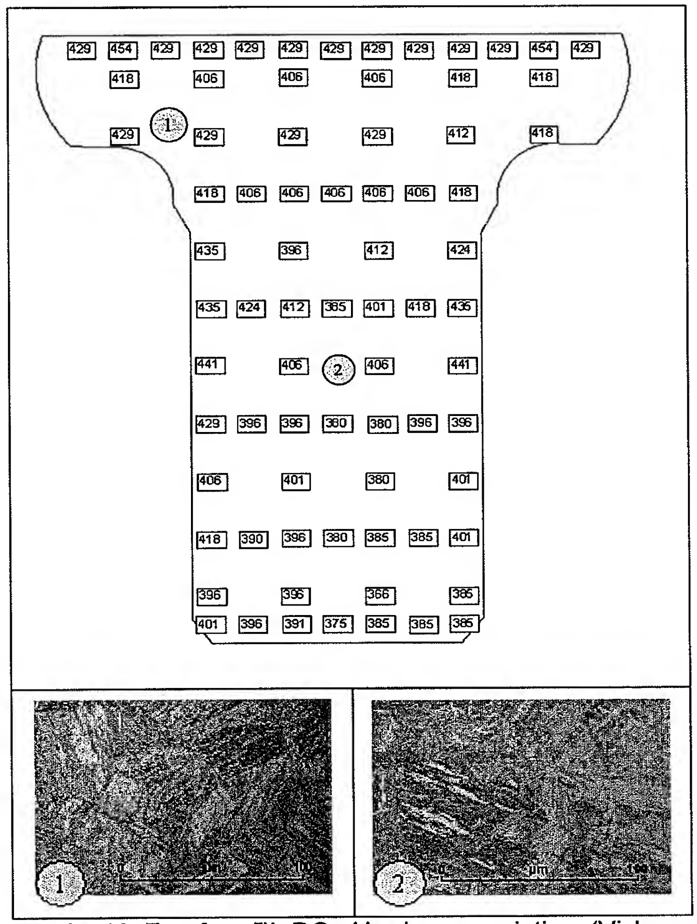


Table 19 Freeform™ DQ: Hardness variation (Vickers test HV30) and microstructure of the forged part quenched in water.

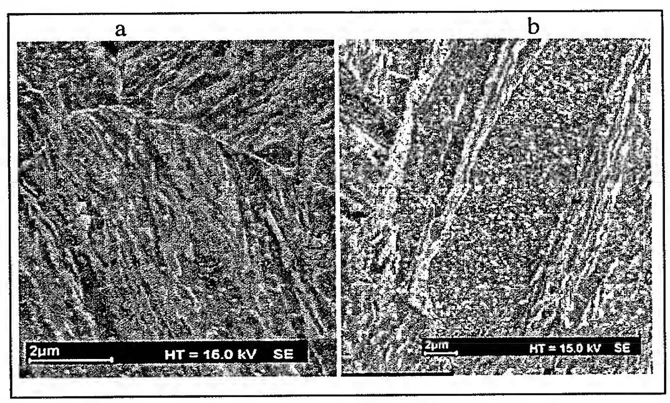


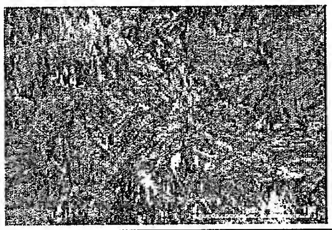
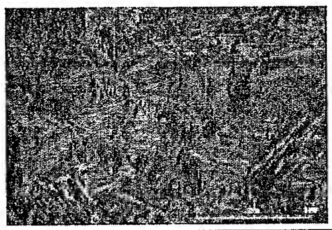
Table 20 :Freeform™ DQ Microstructure of the forged part with lower bainite with (a) auto-tempered martensite (b) laths observed by SEM FEG microscopy.

The FEG-SEM investigations (Table 20) showed that the homogeneous structure obtained consists to a large degree of lower bainite (bainite III). Nevertheless, it was also observed that some laths were identified as auto-tempered martensite. These were distinguished from lower bainite by the presence of particles having more than one orientation inside the laths.

Supplementary trials have been carried out directly on a Ø 50 mm (2.0 inches) cylindrical blank that was quenched with the same quenching fluids.

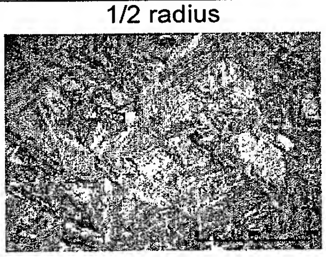
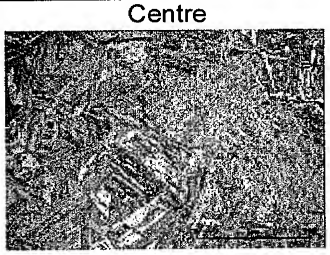
The results are very similar to those obtained on the Ø 40 mm (1.57 inches) forged part when comparing the structure and the mechanical behavior (Tables 21 and 22).

This shows that the Freeform™ DQ grade is particularly adapted to the production of components with significantly larger cross sections.

1/2 radius	Centre
	

UTS MPa	YS MPa	El %	RA %	Hardness HV30		KV J/cm²	
1050	915	16	74	min.	308	20°C	110
				max.	343		

Table 21: Behavior of the Freeform™ DQ grade with a blank diameter of Ø 50 mm direct quenched in oil.

1/2 radius	Centre
	

UTS MPa	YS MPa	El %	RA %	Hardness HV30		KV J/cm²	
1200	975	16	72	min.	375	20°C	100
				max.	406		

Table 22: Behavior of the Freeform™ DQ grade with a blank diameter of Ø 50 mm direct quenched in water.

CONCLUSION

The Freeform™ grades that have been developed by Mittal Steel represent a new family of niobium microalloyed low carbon bainitic steels designed for the production of high strength, high toughness components through cold heading, cold forging or hot forging without final heat treatment.

These steels offer a solution that is well adapted to the manufacture of components demanding a combination of high strength, ductility and toughness.

The possibility offered by these grades through the achievement of a bainitic microstructure, even at low cooling rates, extends the range of the part sizes that can be produced. In the case of hot forging and direct quenching, it also enables the use of quenching media less drastic than water, such as oil, polymers or, possibly air, and thus reduces the associated problems of distortion, cracking, etc.

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